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THE EFFECT OF MECHANICAL DAMAGE ON FRACTURE INITIATION IN LINE PIPE PART I - DENTS

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THE EFFECT OF MECHANICAL DAMAGE ON FRACTURE INITIATION IN LINE PIPE PART I - DENTS

by

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ABSTRACT

Dents are a type of damage that occurs frequently to pipelines. Present specifications allow dents up to a maximum of 2% of pipe diameter. In this study dents with a depth up to 6.89% of the pipe diameter were pressure tested to simulate both hydrostatic proof test, and the most severe operational conditions. Cracks were observed in one dent close to sharp corners where recovery was restricted. Cracks were not observed in other dents, even after pressurisation to 110% of the actual yield stress followed by up to 10,000 cycles of loading to 80% of the yield stress. Further work to illumine the effects of dents with sharp corners, metallurgical changes, and thickness reduction is necessary.

L'EFFET DE L'ENDOMMAGEMENT MÉCANIQUE SUR L'INITIATION DES FISSURES DANS LES TUBES POUR CANALISATIONS: PARTIE I - LES RAINURES

par

K.C. Wang et E.D. Smith

RÉSUMÉ

Les rainures sont un type de dommage fréquemment observé sur les canalisations. Les normes actuelles sur les tubes pour canalisations tolèrent des rainures d'une profondeur maximum de 2% du diamètre du tube. Dans cette étude, des tubes ayant des rainures d'une profondeur de 6.89% de leur diamètre ont été pressurisés pour simuler un essai hydrostatique et les plus sévères conditions d'opération. Des fissures ont été observées près de l'arête aigue d'une rainure qui avait une possibilité de restauration très limitée. Ailleurs, aucune fissure n'a été observée, même après une pressurisation atteignant 110% de la limite d'élasticité, suivie par plus de 10000 cycles à une charge égale à 80% de la limite d'élasticité. Des travaux additionnels sont nécessaires pour élucider les effets des rainures ayant des arêtes aigues, des changements métallurgiques et de la réduction de l'épaisseur.

INTRODUCTION

In a study of gas pipeline failures between the years 1971 to 1975, it was found that 56% were caused by mechanical damage mostly inflicted on pipes by construction equipment (1). Specifications (2,3,4) which limit allowable damage to pipelines are thus very stringent. If dents over 2% of the pipe diameter in depth are inflicted, a cylindrical section of the pipe containing the dent must be replaced. If gouges and grooves are present, they may be ground out, but only if the remaining thickness of the pipe wall exceeds the minimum.

The current trend is to study the effects of defects in pipelines by fracture mechanics analyses. In conjunction with past experience and laboratory tests, fracture mechanics can lead to a better understanding of failure mechanisms, and hence, to the design and manufacture of more reliable and economical pipeline systems.

In previous work, Wade and Walsh (5) tested sections of superficially damaged gas pipe and found the failure stress to be significantly higher than the design stress. Battelle Columbus Laboratories (6-9) have studied defects in pipelines thoroughly. Dents of various shapes and depth were made in pipe specimens which were subsequently burst tested. No pipe failed in a dented region. Fearnehough et al (10) investigated the tolerance of pipelines to mechanical damage and to weld defects. Kasen et al (11) studied three-dimensional blunt defects arising from arc strikes, slag, porosity, etc.

The present report describes the first phase of a long term study on mechanical damage in linepipes, i.e., the behaviour of "pure dent" during monotonic and cyclic loading.

EXPERIMENTAL PROCEDURE

MATERIAL CHARACTERISTICS

Eight specimens from four pipes, were capped, subject to controlled denting, and were pressurized in an MTS closed loop system. The nomenclature for identifying the specimens and the size of the specimens are shown in Table 1. The chemical composition of pipes numbered 8, 12 was determined by emission spectroscopic analysis, whereas the chemical composition of pipes 20H, 20F and 20FT was provided by the supplier from ladle analysis (Table 2).

Transverse tensile specimens were prepared from the pipes according to ASTM Standard A 370. Two-thirds size Charpy specimens were made from pipes 8, 12, 20 F and 20 H, and half-size specimens from pipe 20 FT according to ASTM Standards A 370 and E 23; the results from 20 FT were normalized to the two-thirds size.

SPECIMEN PREPARATION

Reusable caps were welded to the ends of pipe sections whose lengths are shown in Table 1. Caps for the 219 mm and 324 mm diam pipe specimens, were made by welding a short length of the pipe to be tested to a thick circular plate. Forged dome-shaped caps were used for the 508 mm diam pipe. One cap was tapped to make a connection to the hydraulic supply while the other was tapped to bleed entrapped air and connect with a pressure transducer.

Stress analysis indicates that to avoid end, or interference, effects one dent only should be made in a pipe specimen, a minimum of six diameters long. However, at the start of the program, for convenience, and familiarization, tests were performed on a 20 inch diameter pipe specimen that was only three diameters long, 20H-1. In the interests of expediting the work, subsequently, more than one dent was impressed in all full length pipe specimens. See Table 1.

DENTING

Indenters of four different sizes (Fig. 1) were used to make dents. These were a 12.7 mm x 50.9 mm rectangular bar, rods 133.4 mm diam x 51 mm long and 107 mm diam x 203 mm long, and a tooth 12 mm x 122 mm from an excavating machine. The ends and edges of the indenters except those of the tooth were sufficiently rounded to prevent sharp indentations from forming. The pipes were indented in a hydraulic press.

INSTRUMENTATION

To measure the deformation during monotonic and cyclic loading, strain gauges were mounted in the dents and on strain free material away from the dent in both longitudinal and circumferential directions. A linear variable displacement transducer (LVDT) was mounted in the centre of a dent to measure vertical displacement. Acoustic emission (AE) transducers were

mounted at both ends and in the centre of each pipe specimen to locate and monitor crack growth. The outputs from strain gauges, LVDT and AE transducers were all recorded on strip-chart and X-Y recorders.

TEST PROCEDURE

Two test sequences were used to pressure test pipe specimens. To simulate damage during or before construction, specimens were pressurized to 110% of yield stress and fatigue tested to 80% yield equivalent up to 10,000 cycles. To simulate damage during operation, dents were formed after the hydrostatic test and specimens then fatigue tested up to 10,000 cycles. Pipe specimens were reproofed by pressurizing to 110% yield equivalent following fatiguing.

PRESSURIZATION

An MTS closed loop system was used together with a pressure intensifier to supply a water-glycol mixture at pressures up to 55 MPa to test pipe specimens.

For proof testing, the pressure was increased monotonically to 110% yield stress level in 8 minutes. A slight deviation from linearity was noticed as the pipe wall yielded. During cyclic loading, pipes were pressurized at rates of between 0.016 Hz (1 cycle/min) and 0.0083 Hz (1 cycle/2 min) depending on the pipe size.

ACOUSTIC EMISSION

A Dunegan/Endevco acoustic emission (AE) detection unit was used to monitor deformation processes and crack propagation. Individual and/or cumulative signals were detected with a S 140 B transducer mounted close to the dent. Two other S 140 B transducers (connected to a D/E 902 linear flaw locator) were mounted one at each end of the pipe. The flaw locator - an early model - was not very effective.

RESULTS

MECHANICAL PROPERTIES

The mechanical properties of tensile specimens of flattened pipe and the impact energy at room temperature of 2/3 size Charpy specimens are shown in Table 3. The 0.5% yield strength of pipe specimens obtained from hydrostatic testing and tensile testing are shown in Table 10.

PIPE SPECIMEN 8-1

This specimen was dented to a depth of 7.26 mm with indenter B (Fig. 1), then pressurized to 110% of its yield equivalent. The hoop strain in the dent (ϵ_{hd}) and pipe (ϵ_{hp}) during pressurization are shown in Fig. 2. The strain gauge in the dent failed at 6.71%, at which point the strain in the pipe was 1.49%. A new gauge was mounted and the specimen pressurized to 110% yield equivalent for 24 h. An inadvertent pressure pulse to 119% yield equivalent led to a strain of 8.61% in the dent and 2.78% at a point removed from it. No further increase in strain was noticed in the remaining pressure holding period and in the subsequent fatigue test to 80% of the yield equivalent. The results are shown in Table 4.

PIPE SPECIMEN 12-1

This specimen was dented with indenter B (Fig. 1) to a depth of 5.1 mm. The pipe was then pressurized to 24.6 MPa (hoop stress σ_{hp} = 418.4 MPa, yield stress σ_y = 401 MPa) and held at this pressure for 24 h. The hoop strain in the dent and in the pipe wall at this time are shown in Fig. 3. The hoop strain in the pipe wall (ϵ_{hp}), initially 0.233% at 24.6 MPa, increased to 0.5% after 44 min and to 0.6% after 6 h. Subsequent fatigue testing at 17.9 MPa (ϵ_{hp} = 304.3 MPa) did not cause any further plastic deformation either in the dent or the pipe wall. An increase in pressure to 28.27 MPa (σ_{hp} = 480 MPa) for 10 min produced a substantial strain increase in both the dent and in the pipe wall (Fig. 4). (Readings of strain in the pipe wall ceased at 1.52% when the strain gauge failed.)

PIPE SPECIMEN 20 H-1

A shallow dent of 2.72 mm was formed with indenter B (133.4 diam x 51 mm bar). The pipe was pressurized subsequently to 21.84 MPa. The hoop strains in and away from the dent are shown in Table 5. The strain gauges failed after the pressure in the pipe reached 21.80 MPa. New gauges were mounted and the pipe specimen was repressurized to 21.84 MPa and held for 24 h. The strain in and away from the dent increased during the 24 h holding period. Subsequent fatigue testing between 0.69 and 15.88 MPa for 4000 cycles showed no plastic strain in the pipe and only slight plastic strain (0.019%) in the dent.

PIPE SPECIMEN 20 F-1

Two dents 1000 mm from each other and from the girth weld were made in this specimen. One dent was made by indenter B (133.4 mm x 51 mm bar) to a depth of 7.16 mm and the other by indenter C (tooth from an excavating machine) to a depth of 7.85 mm. The volume expansion of the specimen at yield stress exceeded the liquid capacity of the intensifier and, hence a pressure equal to 110% yield equivalent could not be reached without replenishing the liquid in the intensifier. A pressure of 21.84 MPa was eventually applied (the same pressure as was applied to 20 H-1) but an excessive hoop strain of 3.3% was recorded and the test was stopped after a total of 286 min. Subsequent fatigue testing was aborted at the 1667th cycle after a leak was detected at the girth weld between the pipe and an end cap. The results are shown in Table 6.

PIPE SPECIMEN 20 F-2

This pipe specimen was dented with indenter D (101.6 mm diam x 203.2 mm rod) to a depth of 29.6 mm at a point one third the way along its length. A pressure of 19.65 MPa was reached on the first loading. The pipe was pressurized to 21.38 MPa i.e. 110% of 19.44 MPa, the pressure at yield. At the proof pressure, the total hoop strain was 2.35% in the pipe and 13.33% in the dent. The pipe specimen was then fatigue tested between 0.69-15.56 MPa for 8252 cycles at which point a second dent made by indenter D to a depth of 18.9 mm. This dent was placed between the first dent and the further end of the pipe. The pipe was then fatigue tested a further 1127 cycles when a pressure pulse arising from an instability in the pressure intensifier caused the pipe to fail at the seam weld. The strain gauge results from this experiment are shown in Table 7.

PIPE SPECIMEN 20 FT-1

Two dents of depth 25.65 mm and 5.33 mm were impressed in this specimen with indenter B (133.4 mm diam x 51 mm rod). This pipe was stressed to 110% of yield equivalent as determined by 0.5% strain measured in tensile tests of flattened transverse specimens. This procedure was adopted because excessive deformation was observed in specimens 20 F and 20 H pressurized to 110% of yield equivalent based on a 0.5% strain in the pipe wall during pressurization. The pipe specimen was pressurized to 9.81 MPa initially,

then pressurized to 10 MPa, the 110% yield equivalent, and held there for a total of 57 min. It was then fatigue tested for 7800 cycles. The strains in the dents and on the pipe wall are shown in Table 8. A third dent was pressed between the first two dents to a depth of 29.59 mm with indenter D (1016 mm diam x 203.3 mm rod). The pipe specimen was then pressurized to 110% of yield equivalent. The longitudinal contours of the third dent before and after the pressure test are shown in Fig. 5. The centre of the dent almost completely recovers its original contour. The corners of the dent do not recover completely because the radius of curvature of the ends of the indenter is small. However, examination did not reveal any cracks in this region.

PIPE SPECIMEN 20 FT-2

This specimen was dented to a depth of 21.26 mm with indenter B (133.4 mm diam x 51 mm rod) one third along the length of the pipe. The pipe was pressurized to 10 MPa at which pressure the hoop strain was 1.67% in the pipe and 7.32% in the dent. A second dent was pressed into the pipe to a depth of 32.16 mm with indenter D (101.6 mm diam x 203.2 mm rod). The second dent was located between the first dent and the further end of the pipe and was offset 45 degrees radially. The pipe was then fatigue tested for 3000 cycles. The hoop strains developed during testing are shown in Table 9. The cyclic strains in dent 1, dent 2 and in the pipe wall at the 2150th cycle are shown in Fig. 6. Although dent 1 (Type B) had been pressurized previously to 110% of yield equivalent, the strain range was higher for dent 1 than for dent 2 (Type D). However, the plastic strain associated with each cycle is higher for dent 2 than for dent 1. The contour of dent 2 is shown in Fig. 7. Most of the dent was pushed out during the first cycle on pressurizing to 80% of yield equivalent and further recovery during the subsequent 3,000 cycles was slight.

A third dent was impressed with indenter C between the first two dents to a depth of 25.5 mm; the third dent was offset 22.5 degrees radially from the first two. The specimen was fatigue tested for 1500 cycles to 80% of the yield stress and then pressurized to 110% yield stress. The total hoop strain in the third dent exceeded 1.72% before the strain gauge failed at a pressure close to the 110% yield stress. The hoop strains on the pipe and in the centre of the second dent were 0.18% and 0.925%, respectively.

There was no permanent strain on the pipe wall but 0.66% residual strain remained in the second dent.

Fatigue testing to 80% yield stress was continued and AE activity was observed at the 115th cycle. Acoustic emission became continuous after the 146th cycle. The test was stopped and the pipe was examined. There was no surface crack on the third dent. Cracks were observed in the second dent 25 mm from each end of the dent. The main source of AE came from a small leak at the girth weld where fluid under pressure sprayed out as a mist. Radiography, magnetic particle inspection, ultrasonic and liquid penetrant methods failed to locate this leak at the girth weld after the fluid was drained.

PIPE SPECIMEN 20 FT-3

This specimen was dented and pressure tested in a similar fashion to pipe specimen 20 FT-2, but no cracks were found in dent 2 of 20 FT-3 at the end of the test.

ACOUSTIC EMISSION

A typical cumulative acoustic emission (AE) count during pressurization of a pipe specimen containing dents is shown in Fig. 8. The fairly uniform increase in AE output illustrated in the Fig. coincided with plastic deformation in the dents which began at low pressure. There was no marked increase in AE activity when the pipe reached yield point.

Pipe specimen 20 F-1 developed a leak at the girth weld joining an end cap to the pipe. Figure 9(b) shows the AE activity rate of 20 F-1 plotted against pressure during the fatigue test. The sharp increase in AE activity at high pressure indicates the start of leakage. Figure 9(a), which is a cumulative plot, shows that acoustic emission continues as the pressure drops until the pressure falls to one fifth of maximum.

DISCUSSION

YIELD STRESS

The yield stress used in specifications by the pipeline operating companies and the linepipe manufacturers is the transverse stress at 0.5% strain. Either cold flattened transverse specimens or ring specimens, as per

ASTM A370, can be used to determine the yield stress. The yield stress determined by tensile testing a cold flattened specimen (Y_{ST}) varies only by 1% from that determined by the ring expansion method (Y_{PV}) (14). Results for pipes tested in this study are shown in Table 10. (The lower value of Y_{ST} at 418 MPa for pipes 20 H and 20 F was provided by the pipe manufacturer in 1973, while the higher value of 481 MPa was measured in 1979. The 13% difference could have resulted from strain aging as the pipes were cold expanded in the mill.)

As Table 10 shows, the ratio of Y_{ST}/Y_{PV} varies between 0.78 and 1.04. (The spread of the ratios varies between 0.88 and 1.04 if the lower values of Y_{ST} for 20 F-1, 20 F-2 and 20 H are disregarded and only current measured values are selected.) Maxey (14) compared yield stresses measured by different methods and found the average ratio of Y_{ST}/Y_{PV} to be 0.91 with a standard deviation of 7.8% and a maximum deviation of 23.1%. The results of Table 10 show an average ratio of 0.937 with a standard deviation of 5.93% and a maximum deviation of 11% in good agreement with Maxey's measurement (14).

RECOVERY OF DENTS DURING PRESSURIZATION

When an indenter is pressed into a pipe, the pipe material conforms to the shape of the indenter, deforming elastically and/or plastically depending on the depth of the dent and the morphology of the indenter. Dents formed with indenter A in Fig. 1 undergo high plastic deformation because strain is distributed over a small area. Dents formed with indenter B in Fig. 1 have strains spread over a wide area. In deep dents formed with indenters B and D, large local deformations occur at the ends of the indenters.

During pressurization, the centre of a dent can start to yield at a pressure as low as 13% of the general yielding pressure (P_{YS}). The hoop strain in the dent (ϵ_{hd}) increases slowly as the pressure begins to increase and increases more rapidly as the pressure approaches the yield stress, Fig. 10.

In the elastic range, the hoop strain in the pipe wall (ϵ_{hp}) increases slowly and linearly with increase in pressure but increases rapidly as the yield point is approached or exceeded. Straining (in both pipes and dents) continues when the pressure is held at 110% yield stress, but eventually, drops to zero.

In general, the centre of a dent almost recovers its original contour when a pipe is pressured to 110% yield stress. However, the ends of deep dents formed by indenter D never fully recover (Fig. 5, 7).

The strains developed in dents pressured to 110% stress level are shown in Table 11. Hoop strains in a dent are plotted against the depth of dent/pipe diameter ratio (Fig. 11) and a linear regression analysis of the data is shown in Table 12. The data yield correlation coefficients between 0.79 and 0.94 depending on the data points selected. An equation relating hoop strain in the dent (ϵ_{hd}) at 110% yield pressure to the dent depth/pipe diameter (D/2R) ratio can be expressed as follows:

$$\epsilon_{hd}(\%) = 1.69 \left(\frac{D}{2R}\right) + 2$$

ϵ_{hd} and D/2R are dimensionless and are expressed as percentage. ϵ_{hd} is the hoop strain in the dent. D is the depth of a dent and 2R is the pipe diameter.

Whereas, the longitudinal strain in a pipe wall is always tensile, the longitudinal strain in the centre of a deep dent can be compressive. In these circumstances, the strain passes through a (compressive) maximum as pressure is applied in the pipe and then falls in value, eventually becoming tensile, if the pressure becomes high enough.

STRAIN AMPLIFICATION DURING MONOTONIC PRESSURIZATION

During initial hydrostatic pressure testing, the material in a dent reaches its yield point before material in the undeformed pipe. Material in long and/or deep dents reaches its yield point earlier and has higher deformation in the circumferential direction. The hoop strain in a dent (ϵ_{hd}) can initially be much higher than the hoop strain in the pipe wall (ϵ_{hp}), but the $\epsilon_{hd}/\epsilon_{hp}$ ratio decreases rapidly once the pressure at which yield takes place is reached. The strain amplification $\epsilon_{hd}/\epsilon_{hp}$ versus normalized pressure is shown in Fig. 12. Dent 20 F-2 formed by indenter D (101 mm diam x 203.2 mm long) has a much higher strain amplification than dents formed with indenter B (133.4 mm diam x 51 mm long).

HOOP STRAIN AMPLIFICATION DURING CYCLIC LOADING

Some dents and gouges can survive an initial hydrostatic proof testing but fail after a period of operation. Cracks can initiate during proof testing and grow during subsequent pressure fluctuations. The strain range in defects associated with dents during cyclic loading can differ significantly from the nominal strain range in the pipe wall.

Canadian specifications for operating pipelines require the maximum operating pressure not exceed 80% specified minimum yield stress. In the present series of tests, stressing ranged from a low of 3.1% YS for specimen 12-1 and 7.6% YS for specimen 20 FT, to a upper limit of 80% YS. Specimens sustained loading sequences between 3000 cycles to 12000 cycles. These test conditions are more severe than a pipeline would be subject to in an operational lifetime of 30 years.

After the initial pressurization to 110% or 80% YS, the hoop strain in the pipe wall varies between 0.11% and 0.188% during the subsequent cyclic loading whereas the hoop strain in a dent can vary as much as 0.22% to 0.49% depending on the initial dent depth and morphology. Results from the tests illustrate this point in Table 13. Dents with a high dent depth/pipe diameter (D/2R) ratio will have high cyclic strain amplification as will dents that have not been pressurized to 110% YS. Short localized dents will have higher cyclic strain amplification than long dents.

HOOP STRAIN INCREASE IN THE DENT DURING CYCLIC LOADING

Dents during the initial hydrostatic proof test can be shaken down if the initial dent depth is small. The shake-down effect has generally been used in proof testing pressure vessels. Joints, openings and other locations of high stress concentration will yield locally during proof testing and subsequently, will experience elastic stress only at the lower operational pressures if shake-down has occurred. Otherwise plastic strain will accumulate in each pressure cycle. The results of present tests are shown in Table 14. Pipe specimens 8-1, 12-1 and 20F-1 did not show any plastic strain during cyclic loading. Dent 20F-2-2 had the highest plastic strain per cycle. At a strain of 9.14×10^{-6} per cycle, the dent accumulated 2.8% plastic strain in 3000 cycles of loading but because the pipe was not pressurized to 110% YS, the dent should accommodate this strain without failure.

STRAIN AMPLIFICATION IN RESTRICTED ENDS

Dent 20 FT-2-2 was formed on specimen 20 FT-2 after the first dent, 20 FT-2-1, had been proof tested. These two dents, offset 45° radially, were located 914 mm from each other and from the girth weld at the end. After the pipe had been stressed for 3000 cycles, a third dent, 20 FT-2-3, was formed between the first two and offset 22.5° from each. After a further 1500 cycles, cracks were observed at both ends of dent 20 FT-2-2, as shown in Fig. 13. Dent 20 FT-3-1 was formed on pipe specimen 20 FT-3 and tested to duplicate 20 FT-2-2. No cracks were observed. Dent 20 FT-3-2 was pressurized to 80% YS in 15 second, again, no cracks were observed. The strains on 20 FT-3-1 were monitored during cyclic loading and are shown in Fig. 14. The hoop strain in the centre of the dent ϵ_{hd}, was much less than the hoop strains 25 mm from each end - ϵ_{hd}' and ϵ_{hd}'' during cyclic loading where cracks were observed in 20 FT-2-2.

Though cracks in dent 20 FT-2-2 cannot be reproduced at dents 20 FT-3-1 and 20 FT-3-2 that were pressurized under similar conditions. Regions around a sharp dent that do not recover their original contour are prone to fatigue failure because of their higher strain amplification.

CONCLUSIONS

Pipe specimens with dents of different geometry and depth were tested to simulate both hydrostatic proof testing and a subsequent cyclic loading require. Cracks were found at one dent in one pipe specimen. The cracks were located close to both ends of a long dent where large local deformation had occurred. No other dents, including dents formed with an excavating tooth, showed cracks during the testing. The results of this program can be summarized as follows:

1. During initial pressurization deep dents experience higher hoop strains than shallower dents. An empirical equation relates hoop strain to dent-pipe geometry:

$$\epsilon_{hd}(\%) = 1.69\,(\frac{D}{2R}) + 2$$

2. Long dents experience higher hoop strains than the short dents during initial pressurization. Short dents undergo higher strain amplification during cyclic loading.

3. Dents with sharp radii of curvature do not recover their original contour during initial pressurization and experience high strain amplification during cyclic loading.
4. Dents formed after proof testing have a higher hoop strain range during cyclic loading than dents previously proof tested. The total plastic strain accumulated during cyclic loading is less than or approaches the plastic strain developed during proof testing.
5. Dents free of sharp corners will not degrade the integrity of pipelines. However, dents with sharp corners, or dents in which metallurgical changes or thickness reductions have taken place do degrade pipelines. The extent of this degradation will be studied further.
6. Dents with smooth contours impressed to depths up to 6.89% of pipe diameter were pressurized to 110% yield equivalent and cyclically loaded up to 10000 times without failure.

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Table 1. Nomenclature and dimensions of tested pipe specimens.

Specimen No.	Diameter mm	Length, mm			Wall thickness, mm	
		Centre section	End cap	Total	Nominal	Measured
8-1	219	1.200	210	1640	8.18	8.00
12-1	324	1.830	159	2150	9.53	9.70
20 H-1[a]	508	1.520	508	2540	9.53	9.65
20 F-1[b]	508	2.900	508	3910	9.53	9.65
20 F-2[b]						
20 FT-1[c]	508	2.900	508	3910	5.56	5.59
20 FT-2[c]						
20 FT-3[c]						

a) H designates specimens of "half" length i.e. three times pipe diameter

b) F designates specimens of "full" length i.e. six times pipe diameter

c) FT designates thin wall, full length specimens

Table 2. Chemical composition of pipe specimens

Pipe No.	Composition wt%							
	C	Mn	P	S	Si	Cb	Cr	Ce
8	.175	.86	.006	.028	.04	-	.71	
12	.10	.92	.007	.026	.12	.03	.11	
20 H and 20 F	.19	1.09	.007	.013	.20	0.01	-	
20 FT	.18	.72	.006	.028	.06	-	.06	.30

Table 3. Mechanical properties of pipes.

Pipe No.	Yield strength (YS) MPa	Tensile strength (UTS) MPa	$YS/_{UTS}$	Elongation %	2/3 C_v J
8	379	455	0.83	27	-
12	401	475	0.84	33	30
20 H and F	418	567	0.74	34	25
20 FT	415	520	0.8	28	21*

*Calculated from the results of half-size specimens

Table 4. Pressure testing of pipe specimen 8-1

Monotonic loading.

Time h	Pressure MPa	Circumferential strain, %	
		pipe	dent
0	29.6	1.49	6.68
0.5	29.6	1.54	7.52
8.5	29.6	1.59	7.91
13.5	29.6	1.59	8.61
13.5	31.9	2.78	9.03
24	29.6	2.79	9.04

Cyclic loading

Cycle No.	Pressure range, MPa	Circumferential strain %		
		Pipe $\Delta\varepsilon_{hp}$	Dent $\Delta\varepsilon_{hd}$	$\Delta\varepsilon_{hd}/\Delta\varepsilon_{hp}$
1	1.38-21.5	0.12	0.23	1.92
10000	1.38-21.5	0.12	0.23	1.92

Table 5. Pressure testing of pipe specimen 20H-1

Monotonic loading.

Time, h	Pressure MPa	Hoop strain %	
		Pipe ε_{hp}	Dent ε_{hd}
0	21.84	2.44*	3.74*
0	21.84	0.324	0.376
24	21.84	0.733	1.265

Cyclic loading

Cycle No.	Pressure range, MPa	Hoop strain range %		
		Pipe $\Delta\varepsilon_{hp}$	Dent $\Delta\varepsilon_{hd}$	$\Delta\varepsilon_{hd}/\Delta\varepsilon_{hp}$
50	0.69-15.88	0.188	0.214	1.14
4000	0.69-15.88	0.188	0.215	1.14

Table 6. Pressure testing of pipe specimen 20 F-1
Monotonic loading.

Time, min.	Pressure MPa	Hoop strain, %		
		Pipe ϵ_{hp}	Dent 1 ϵ_{hd_1}	Dent 2 ϵ_{hd_2}
0	18.96	0.197	2.73	>2.47
0	20.13	0.885	X	1.235
0	21.84	2.13	X	X
5	21.84	2.31	X	X
75	21.84	2.42	0.497	0.517
230	21.84	2.93	1.253	1.15
280	21.84	3.30	1.674	1.838

Cyclic loading

Pressure range MPa	Hoop strain, %				
	$\Delta\epsilon_{hp}$	$\Delta\epsilon_{hd_1}$	$\Delta\epsilon_{hd_2}$	$\Delta\epsilon_{hd_1}/\Delta\epsilon_{hp}$	$\Delta\epsilon_{hd_2}/\Delta\epsilon_{hp}$
0.69-15.88	0.174	0.2112	0.2007	1.21	1.15

Table 7. Pressurization test of pipe specimen 20 F-2
Monotonic loading.

Pressure MPa	Hoop strain, %		
	Pipe ϵ_{hp}	Dent 1 ϵ_{hd_1}	Dent 2 ϵ_{hd_2}
19.65	.572	9.9	
21.2	2.35	13.33	
15.56	-	-	9.156

Cyclic loading

Cycle No.	Pressure range, MPa	Hoop strain range %		
		Pipe $\Delta\epsilon_{hp}$	Dent 1 $\Delta\epsilon_{hd}$	Dent 2 $\Delta\epsilon_{hd/2}$
20	0.69-15.56	2.089-2.257	0.031-0.337	
1000	0.69-15.56	2.111-2.283	0.12-0.429	
2000	0.69-15.56	2.121-2.292	0.185-0.496	
4000	0.69-15.56	2.175-2.343	0.285-0.6	
6000	0.69-15.56	2.195-2.369	0.371-0.687	
8000	0.69-15.56	2.24-2.407	0.478-0.793	
8253	0.69-15.56	-	-	0.49-9.156*
8300	0.69-15.56	2.09-2.251	0.498-0.815	9.306-9.797
8770	0.69-15.56	2.1-2.26	0.523-0.84	0.379-0.8175+
9280	0.69-15.56	2.1-2.257	0.553-0.874	0.743-1.177
9760	0.69-15.56	2.1-2.26	0.577-0.903	1.115-1.557
10270	0.69-15.56	2.096-2.26	0.603-0.926	1.615-2.05
10760	0.69-15.56	2.092-2.25	0.624-0.947	2.067-2.5
11270	0.69-15.56	2.096-2.26	0.662-0.985	2.98-3.42

*Gauge failure

+Readings on new gauge

Table 8. Pressure testing of pipe specimen 20 FT-1
Monotonic loading.

Pressure MPa	Hoop strain, %			
	Pipe ϵ_{hp}	Dent 1 ϵ_{hd_1}	Dent 2 ϵ_{dh_2}	Dent 3
9.81	1.187	4.925	2.544	
10	1.52	-	-	
7.27	0.1125*	-	-	11.01
10	0.17*			11.678

Cyclic loading

Cycle No.	Pressure range, MPa	Hoop strain range %				
		$\Delta\epsilon_{hp}$	$\Delta\epsilon_{hp_1}$	$\Delta\epsilon_{hd_2}$	$\frac{\Delta\epsilon_{hd_1}}{\Delta\epsilon_{hp}}$	$\frac{\Delta\epsilon_{hd_2}}{\Delta\epsilon_{hp}}$
100	0.69-7.27	1.295-1.416	0.0863-0.406	0.04-0.254		
550	0.52-7.27	1.295-1.422	0.145-0.489	0.04-0.263		
1000	0.52-7.27	1.295-1.419	0.2-0.553	0.047-0.27		
2000	0.69-7.27	1.314-1.435	0.403-0.743	0.084-0.296		
4000	0.69-7.27	1.311-1.129	0.695-1.039	0.09-0.3		
6000	0.69-7.27	1.317-1.432	1.164-1.517	0.103-0.313		
7800	0.69-7.27	1.311-1.429	1.782-2.135	0.111-0.32	3.07	1.82

* new strain gauge

Table 9. Pressurization test of pipe specimen 20 FT-2

Monotonic loading.

Pressure MPa	Hoop strain, %		
	ϵ_{hp}	ϵ_{hd_1}	ϵ_{hd_2}
10	1.67	7.32	-

Cyclic loading

Cycle No.	Pressure range, MPa	Hoop strain range, %		
	$\Delta\epsilon_{hp}$	$\Delta\epsilon_{hd_1}$	$\Delta\epsilon_{hd_2}$
20	0.69-7.39	0.0184-0.139	0.052-0.47	0.204-0.542
100	0.69-7.39	0.0184-0.139	0.054-0.485	0.408-0.678
500	0.69-7.39	0.0184-0.139	0.052-0.501	0.802-1.12
1000	0.69-7.39	0.0184-0.139	0.052-0.523	0.922-1.23
1500	0.69-7.39	0.0184-0.139	0.052-0.53	0.971-1.273
2000	0.69-7.39	0.0184-0.139	0.051-0.532	0.98-1.28
2500	0.69-7.39	0.0184-0.139	0.052-0.534	0.994-1.293
3000	0.69-7.39	0.0184-0.139	0.054-0.544	1.002-1.303

Table 10. Yield stress as determined by the tensile testing of flattened transverse specimens and the pressurization of pipe specimens.

Specimen No.	D mm	t mm	P_{PV}[a] MPa	Y_{PV}[b] MPa	Y_{ST}[c] MPa	Y_{ST}/Y_{PV}
8-1	219.1	8.18	27.28	365	379	1.04
12-1	324	9.53	26.89	457	401	0.88
20-H1	508	9.53	20.13	536.6	481 418[d]	0.90 0.78*
20 F-1	508	9.53	20.06	534.8	481 418[d]	0.90 0.78*
20 F-2	508	9.53	19.44	518.2	481 418[d]	0.93 0.80*
20 FT-1	508	5.56	9.09	446.8[e]	415	0.93
20 FT-2	508	5.56	9.24	422	415	0.98

[a]Pressure at 0.5% total hoop strain on the pipe

[b]Yield stress calculated at 0.5% total hoop strain on the pipe

[c]Yield stress from the tensile test of flattened transverse specimens

[d]Yield stress provided by the pipe manufacturer in 1973

[e]The actual test pressure for this specimen was based on Y_{ST}

*Ratio of Y_{ST}/Y_{PV} using yield stress provided by pipe manufacturer in 1973

Table 11. Strains in dents during pressurizing to 110% YS.

Specimen No.	Dent No.	Diameter 2R mm	Dent depth D mm	Indentor	D/2R %	Hoop strain ε_{hd}, %	Longitudinal strain ε_{hd}, %
8-1	8-1	219.1	7.26	B	3.31	6.68	0.693
12-1	12-1	324	5.1	B	1.57	6.07	-
20-H-1	20 H-1-1	508	2.72	B	0.535	3.74-	-
20 F-1	20 F-1-1	508	7.16	B	1.41	>4.35[b]	1.15
20 F-2	20 F-2-1	508	29.6	D	5.82	13.33	0.239
20 F-2	20 F-2-2	508	18.9	D	3.92	9.156[a]	0.246
20 FT-1	20 FT-1-1	508	25.65	B	5.04	>4.925[b]	0.122
20 FT-1	20 FT-1-2	508	5.33	B	1.05	2.544	0.105
20 FT-1	20 FT-1-3	508	29.59	D	5.82	11.678[a]	-0.176[a,c]
20 FT-2	20 FT-2-1	508	21.26	B	4.19	7.32	-0.183[c]
20 FT-2	20 FT-2-2	508	32.16	D	6.33	b	0.069[d]
20 FT-2	20 FT-2-3	508	25.48	C	5.02	b	-0.038
20 FT-3	20 FT-3-1	508	35	D	6.89	7.82	-0.196[b,c]
20 FT-3	20 FT-3-2	508	34	D	6.69	6	0.195[d]

[a]To 80% YS only

[b]Strain gauge failed

[c]Compressive strain

[d]Compressive strain then tensile strain

Table 12. Linear regression analysis of hoop strain and dent depth/pipe diameter ratio.

Datum No.	Dent No.	$D/_{2R}$ %(X)	ϵ_{hd}, %(Y)
1	8-1	3.31	6.68
1	12-1	1.57	6.07
1	20 H-1	0.535	3.74
4	20 F-2-1	5.82	13.33
5	20 FT-1-2	1.05	2.54
6	20 FT-2-1	4.19	7.32
7	20 FT-3-1	6.89	7.82
8	20 F-2-2	3.92	9.156[a]
9	20 FT-1-3	5.82	11.678[a]

[a] pressured to 80% YS only

Points used	7	6	8	9
Data omitted	8,9	7,8,9	7	-
Correlation coefficient (R)	0.787	0.923	0.94	0.81
Intercept (Y_1)	3.06	1.96	2.01	3.0
Slope (m)	1.116	1.69	1.69	1.23

Table 13. Hoop strain ranges in a dent and in pipe walls during cyclic loading.

Dent No.	Stress range % YS	Strain range, %		Strain amplification $\Delta\varepsilon_{hd}/\Delta\varepsilon_{hp}$	D/2R
		Pipe $\Delta\varepsilon_{hp}$	Dent $\Delta\varepsilon_{hd}$		
8-1-1	5.1-80	0.12	0.23	1.92	3.31 B[c]
12-1-1	3.1-80	0.107	0.22	1.96[a]	1.57 B
20 H-1-1	3.5-80	0.188	0.215	1.14	0.535 B
20 F-1-1	3.5-80	0.174	0.2112	1.21	1.41 B
20 F-2-1	3.55-80	0.168	0.323	1.92	5.82 D
20 F-2-2	3.55-80	0.168	0.44	2.62[b]	3.72 D
20 FT-1-1	7.6-80	0.115	0.353	3.07	5.04 B
20 FT-1-2	7.6-80	0.115	0.209	1.82[b]	1.05 B
20 FT-2-1	7.5-80	0.121	0.418	3.47	4.19 B
20 FT-2-2	7.5-80	0.121	0.339	2.81[b]	6.33 D

[a] After initial pressuring to 100% YS

[b] After initial pressuring to 80% YS

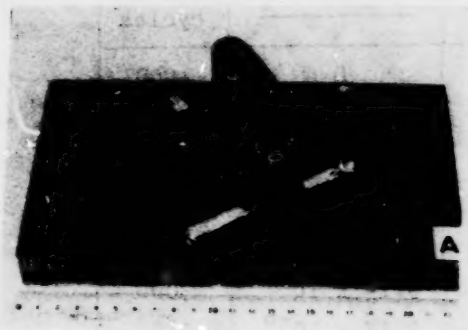
[c] Type of indenter used

Table 14. Hoop strain increase in a dent during cyclic loading.

Dent. No.	D/2R %	Stress range % YS	Strain range %	$\frac{\varepsilon_{hd_N} - \varepsilon_{hd_1}}{N}$	No. of cycles
8-1-1	3.31 B+	5.1-80	0.23	0	1000
12-1-1	1.57 B	3.1-80	0.22	0	1030
20 H-1-1	0.535 B	3.5-80	0.215	1.73×10^{-7}	5000
20 F-1-1	1.41 B	3.5-80	0.2112	0	1665
20 F-2-1	5.82 D	3.55-80	0.323	5.79×10^{-7}	11200
20 F-2-2*	3.72 D	3.55-80	0.44	9.14×10^{-6}	3000
20 FT-1-1	5.04 B	7.6-80	0.353	2.17×10^{-6}	7800
20 FT-1-2	1.05 B	7.6-80	0.209	9.13×10^{-8}	7800
20 FT-2-1	4.19 B	7.5-80	0.418	2.44×10^{-7}	3000
20 FT-2-2	6.33 D	7.5-80	0.339	2.53×10^{-6}	3000

*Initial pressuring to 80% YS

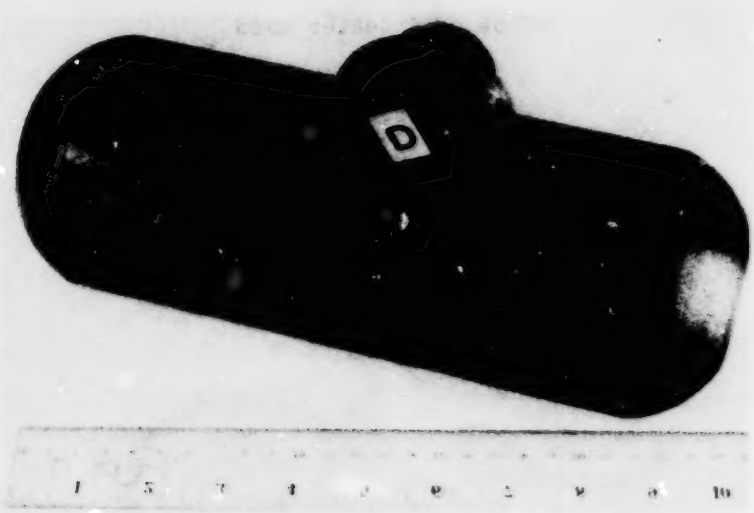
+Type of indenter used



(a)

(b)

(c)



(d)

Fig. 1 - Indenters used to damage linepipe specimens artificially.

(a) 12.7 mm x 50.9 mm rectangular rod (neg 4032)

(b) 133.4 mm diam x 51 mm rod (neg 4031)

(c) Actual tooth from an excavation equipment (neg 4030)

(d) 107 mm diam x 203 mm rod (neg 4029)

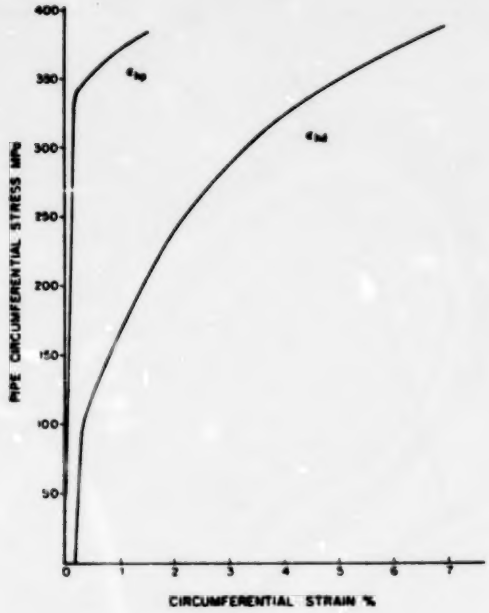
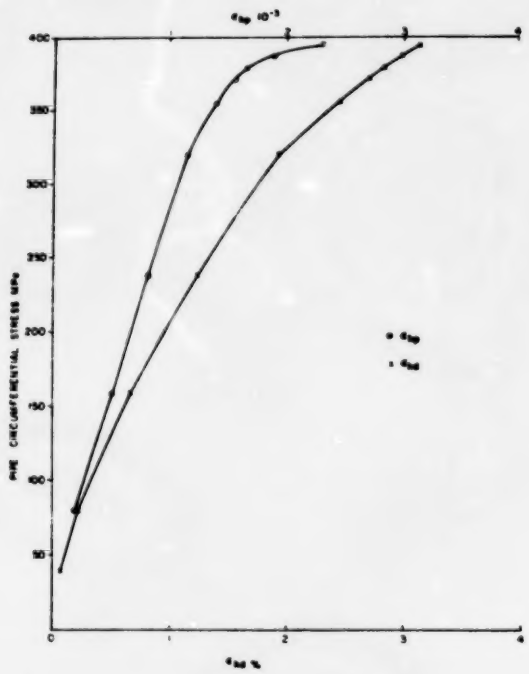
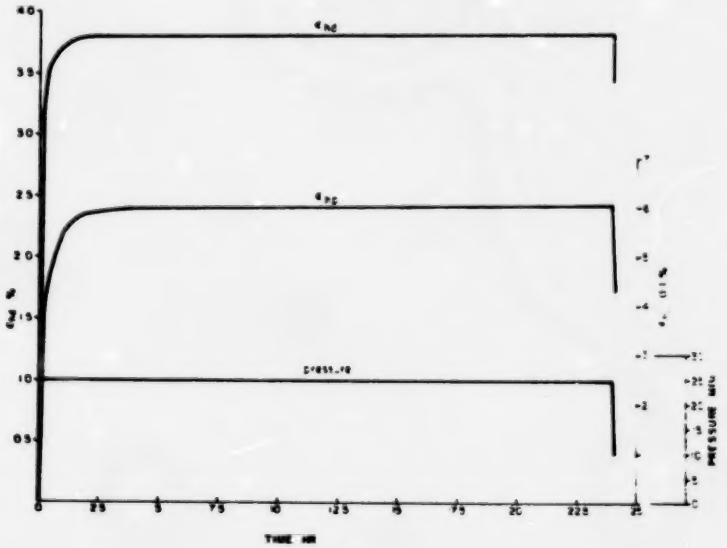


Fig. 2 - The circumferential strain in the dent (ε_{hd}) and on the pipe wall (ε_{hp}) during the pressurization test of pipe specimen 8-1. (neg 4151)



(a)



(b)

Fig. 3 - Hydrostatic pressurization test of pipe specimen 12-1 to 24.6 MPa.
(a) Hoop strain in a dent (ε_{hd}) and in the pipe wall (ε_{hp}) during the initial pressure increase (neg 4146)
(b) 24 h hold (neg 4147)

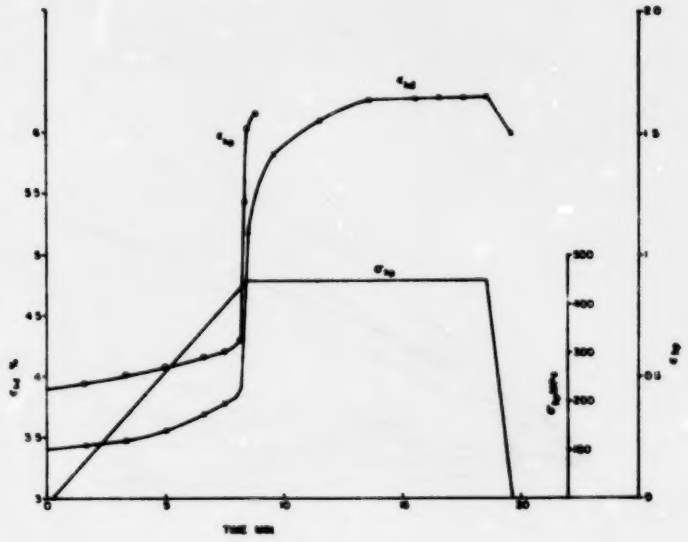


Fig. 4 - Further pressure test of pipe specimen 12-1 to 28.27 MPa. (neg 6165)

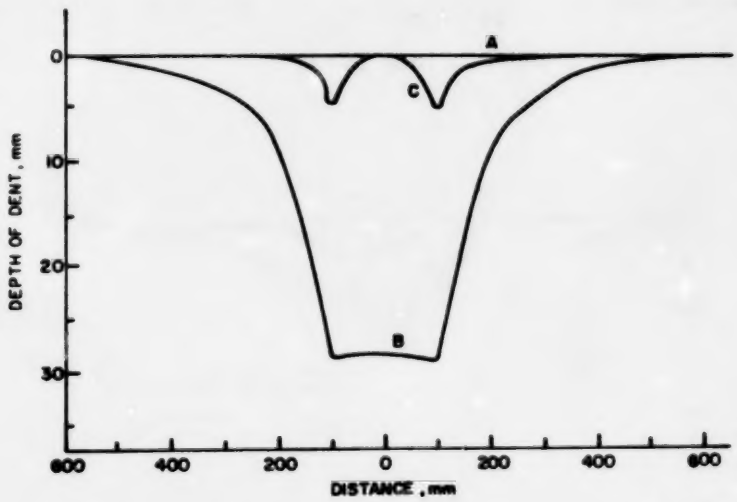


Fig. 5 - The longitudinal contour of the third dent at different stages in pipe specimen 20 FT-1. A. original pipe surface. B. After denting. C. After pressuring to 110% of yield equivalent. (neg 5403)

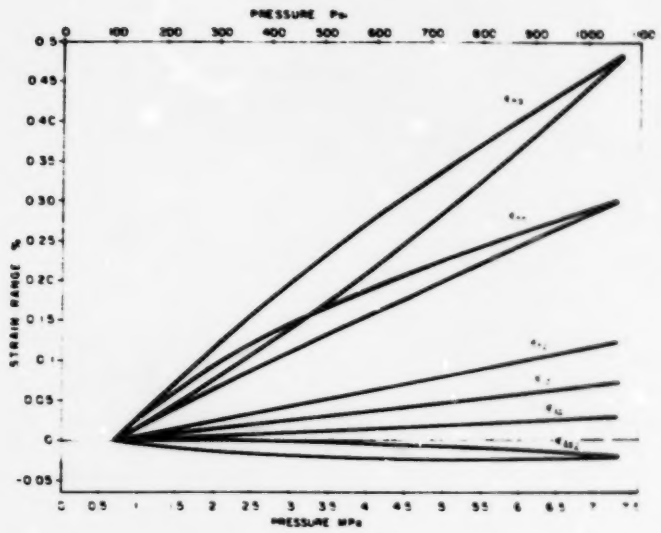


Fig. 6 - Cyclic strains at 2150th cycle during fatigue testing of pipe specimen 20 FT-2. ϵ_{hp}, ϵ_{hd_1}, ϵ_{hd_2} - hoop strain in the pipe wall and in dents 1 and 2. ϵ_{lp}, ϵ_{ld_1}, ϵ_{ld_2} -longitudinal strain in the pipe wall, in dents 1 and 2. (neg 5743)

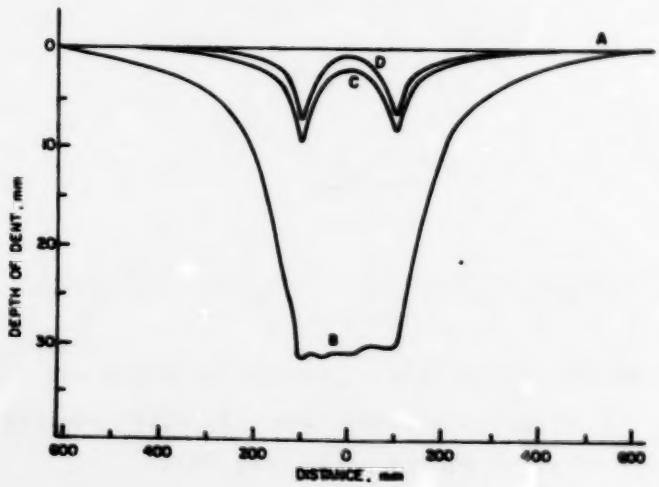
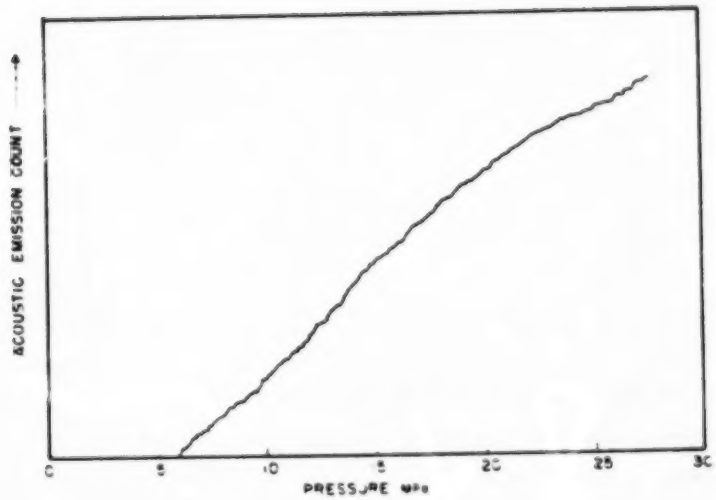


Fig. 7 - Contour of the second dent in pipe specimen 20 FT-2. A. Original pipe surface. B. After denting. C. After the first cycle to 10 MPa (80% YS). D. After the 3000th cycle. (neg 6161)



Pressure ------

Fig. 8 - Cumulative acoustic emission count during pressurization test of pipe specimen 20 FT-1 containing dents.

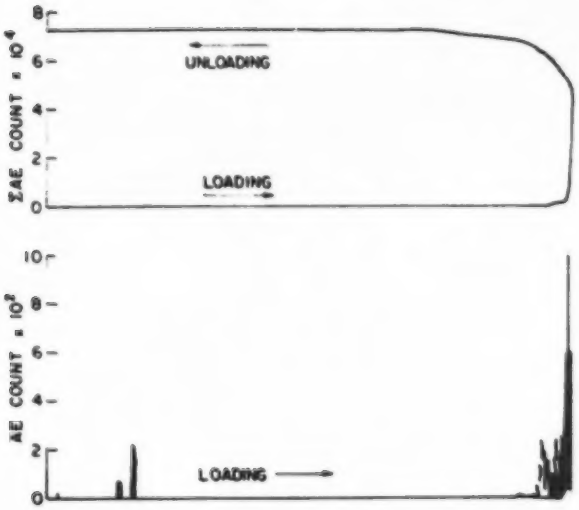


Fig. 9 - Acoustic emission count during fatigue test of pipe specimen 20 F-1 while a leak was developed at the girth weld.

A. Cumulative count, x 10^{-2}

B. Rate count x 1. (neg 6164)

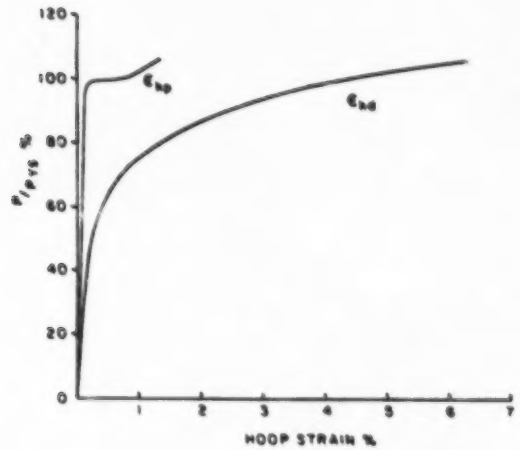


Fig. 10. The hoop strain in the dent and in the pipe wall during initial pressurization of pipe specimen 20 FT-2-1. (neg 6166)

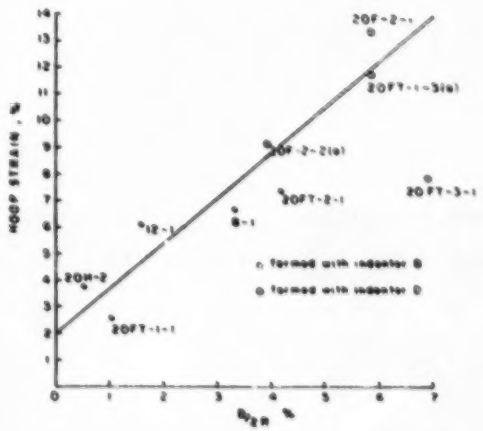


Fig. 11. Hoop strain in the dents vs depth of dent/pipe diameter ratio (D/2R) during initial pressurization test of pipe specimens containing dents. (neg 6167)

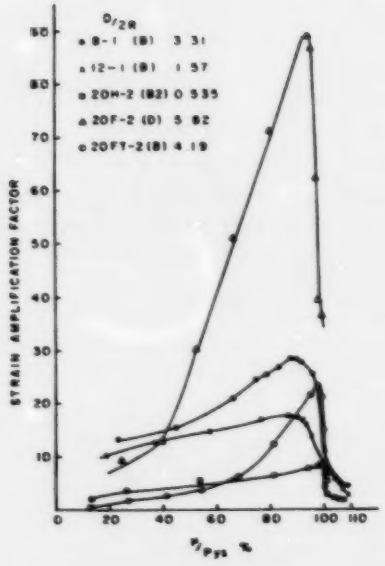


Fig. 12 - Hoop strain amplification ($\epsilon_{hd}/\epsilon_{hp}$) vs normalized pressure during initial pressurization. P_{YS} = pressure at yield point. (neg 6162)

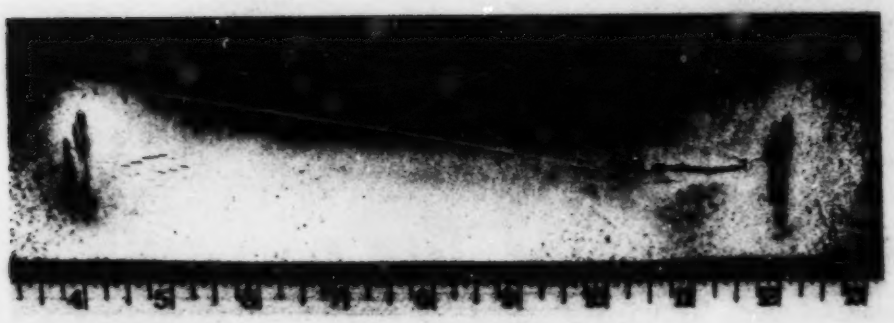


Fig. 13 - Cracks formed at the ends of dent 20 FT-2-2. (neg 4489)

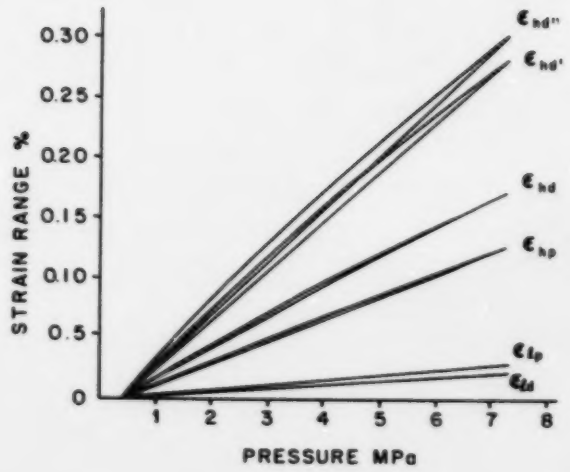


Fig. 14. - Strain ranges in dent 20 FT-3-1 during cyclic loading. Suffix: h - hoop strain; l - longitudinal strain; d - in the centre of the dent; d', d'' - 25 mm from the end of the dent (at the cracked area in Fig. 13). (neg 5744)